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Amazon and the expansion of hydropower in Brazil: Vulnerability, impacts and possibilities for adaptation to global climate change

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ABSTRACT

This article aims to evaluate the use of hydroelectric potential in Brazil and the expansion of the hydroelectric power stations in Amazon, in the northern region of the country, highlighting the vulnerabilities, the impacts and the adaption possibilities of the hydroelectric energy in face to increasing socio-environmental demands and to global climate change in progress. The analysis indicates the nearly exhausted hydroelectric potential in other regions of the country, transforming the Amazon into a new "hydroelectric barn" or "new hydroelectric frontier". The integrated management of reservoirs and multiple uses of water, the new institutional and regulatory arrangements, the technological and economic opportunities of the sector, and finally, integration with neighboring countries are treated to subsidize a sustainable use of hydroelectric potential in the Amazon.

Contents

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1. Introduction

Hydro in Brazil contributes 76.9% of all electricity generated and 15.2% of all domestic energy supply [1]. With 81.9 GW of installed capacity in hydroelectric exploitations [2] and production of 390,988 GW in 2009 [1], Brazil still has a hydroelectric potential of 161 GW, which represents almost two times the hydraulic potential installed. About 63% of this potential is located in the North, mainly in the Amazon basin, which can reduce the exploitation of this potential, by the increasing socio-environmental demands and to global climate change in progress.

From the socio-environmental point of view, there is a tendency for the construction of run-of-the-river hydroelectric power stations, without the existence of pondages, making the values of their power densities (km^2 flooded/MW installed) much lower compared to the plants established in the region in previous decades. Hydropower plants under construction in the Madeira River – Santo Antônio and Jirau – will become run-of-the-river plants, making use of Bulb turbines, used in rivers of low head and large volume of water.

From the standpoint of global climate change, the results released by the Intergovernmental Panel on Climate Change indicate that there is, throughout this century, rising temperatures around the planet. The Amazon and northeastern Brazil constitute what might be called *climatic change hot spots* and represent the most vulnerable regions of Brazil to climate changes. However, the overall picture of changes in rainfall does not always apply to all regions of the Earth. That is the case of Amazon, where all the models project temperature increases, but they do not agree with respect to changes in rainfall patterns.

This article is divided into 6 sections. In Section 2, the theme of hydroelectric generation is presented, highlighting the global and the Brazilian contexts. In Section 3, there is a discussion not extensively, about the regional projections for climate change and its limitations. Section 4 presents the conflicts associated with hydropower projects, especially to the Amazon Basin. Section 5 presents measures of adaptation to the Brazilian hydroelectric system in face of climate change risks. Finally, Section 6 offers conclusions and recommendations.

2. Hydroelectric power: international and Brazilian context

2.1. Existing generation

In 2006, the production of electricity from hydroelectric plants was 32,881 TW h compared to 1295 TW h in 1973 [3], which represented an increase of 154% in this period, and was mainly a result of increased production in China and Latin America, which grew by 460 TW h and 690 TW h, respectively (Fig. 1).

Hydro provides some level of power generation in 159 countries. Five countries make up more than half of the world's hydropower production: China, Canada, Brazil, the USA and Russia. The importance of hydroelectricity in the electricity matrix of these countries is, however, different (Table 1). On the one hand Brazil and Canada are heavily dependent on this source having a percentage share of the total of 83.2% and 58%, respectively. On the other hand United States has a share of 7.4% only from hydropower. In Russia, the share is 17.6% and in China 15.2%.

China, Canada, Brazil and the US together account for over 49% of the production (TW h) of electricity in the world and are also the four largest in terms of installed capacity (GW) [3]. It is noteworthy that five out of the ten major producers of hydroelectricity are among the world's most industrialized countries: Canada, the United States, Norway, Japan and Sweden. This is no coincidence, given that the possibility of drawing on hydroelectric potential was decisive for the introduction and consolidation of the main electro-intensive sectors on which the industrialization process in these countries was based during a considerable part of the twentieth century.

2.2. Deployment: regional aspects

Fig. 2 indicates that despite the significant growth of hydroelectric production, the percentage share of hydroelectricity fell in the last three decades (1973–2006). The major boom in electricity generation has been occurring due to the greater use of gas, and the greater participation of nuclear plants. Coal continues play a major role in the electricity matrix, with a small percentage growth in the 1973–2006 periods, growing from 38.3% to 41%, where is the share of gas-fired power increased from 12.1% to 21.3% in the same period.

Of the world's five major hydroelectricity producers (China, Canada, Brazil, the United States and Russia), only the United States is listed as one of the ten major producers of electricity (consistently among the top 3) using the three fossil fuels, namely coal, combustible oil and gas. China heads the list of producers of electricity from coal, followed by the United States.

Electricity is considered to be one of the most efficient energy carriers given the relative ease with which it can be transported and converted for use. In 2008, of the 8428 Mtoe of final consumption, approximately 17.2% was served by electricity, derived principally from fossil fuels [3].

Although oil accounts for the major share of final consumption electricity is the second largest energy source in 2008, in part due to the increase of electricity generation and consumption in China, principally during the last decade.

In 1973, China represented 2.9% of the worldwide generation of hydroelectricity, but by 2008, its share had grown over fivefold, accounting for 17.8% [3].

2.3. Role of hydropower in the present energy markets

The primary role of hydropower is electricity generation and then its covers all "regular" uses like general demand. Hydro power plants can operate in isolation and supply independent systems, but most are connected to a transmission network. Hydroelectricity is also used for space heating and cooling in several regions. Most recently hydroelectricity has also been used in the electrolysis process for hydrogen fuel production, provided there is abundance of hydro power in a region and a local goal to use H2 as fuel for transport or as a propellant for rockets used in spacecrafts. Hydropower can also provide the firming capacity for intermittent renewable. By storing potential energy in reservoirs, the inherent intermittent supply from variable renewable schemes can be supported. Peak power is expensive. The production of peak load energy from hydropower allows the optimization of base load power generation

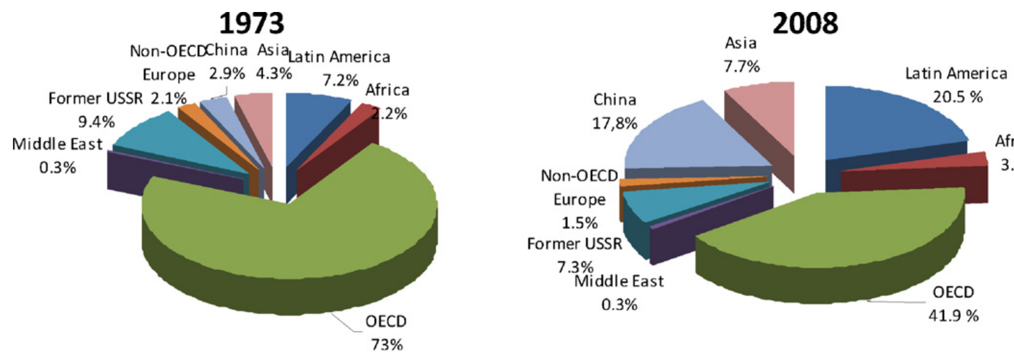


Fig. 1. 1973 and 2006 regional shares of hydro production

Source: IEA [34].

Table 1
Major hydroelectricity producers countries with total installed capacity and percentage of hydro generation.

Country	Installed capacity GW (2007 data)	Country based on top 10 producers	% of hydro in total domestic electricity generation (2008 data)
China	149	Norway	98.5
United States	100	Brazil	79.8
Brazil	77	Venezuela	72.8
Canada	73	Canada	58.7
Japan	47	Sweden	46.1
Russia	47	Russia	16.9
India	36	India	16.0
Norway	29	China	13.8
France	25	Japan	7.7
Italy	21	United States	6.5
Rest of the world	320	Rest of the world[a]	13.6
World	924	World	16.2

Source: IEA [3].
[a] Excludes countries with no hydro production.

from other less flexible electricity sources such as thermal power plants (nuclear, fossil fuels, and biomass). By absorbing excess power, pumped-storage plants enable large thermal power plants to operate at optimum output with high efficiency. Thus, in both a regulated or deregulated market hydropower plays a major role and provides an excellent opportunity for investment. Hydro generation can also be managed to provide ancillary services such as voltage regulation (operating reserves) and frequency control. With recent advances in 'variable-speed' technology, these services can even be provided in the pumping mode of reversible turbines [4].

2.4. Current status of the Brazilian hydroelectric potential

Brazilian hydroelectric potential, as recorded in December 2010 in Eletrobras' Brazilian Hydroelectric Potential Information System (SIPOT) was approximately 243 GW, 36% of which is represented by facilities under construction or in operation [2].

Fig. 3 shows Brazilian hydroelectric potential divided by geographic region [North, Northeast, Mid-West, Southeast and South-trans.]. The potential of each region is described according to the following categories: estimated (*Estimados*), being studied (*Estudos*) and under construction/in operation *(Operação/Construção)*, that is, enterprises which are already operational or will become operational.

Observing Figs. 4 and 5 shown below, one can easily see that the South and Southeast regions together account for 48% of the hydroelectric potential in operation/under construction. On the other hand, the Northern region alone has 45% of the country's hydroelectric potential currently being studied or estimated. This indicates that currently (in the short term), concerns about vulnerability should be focused on the South and Southeast regions, but that in the future the understanding of climate change and its relation to hydroelectric potential should give priority to the Northern region.

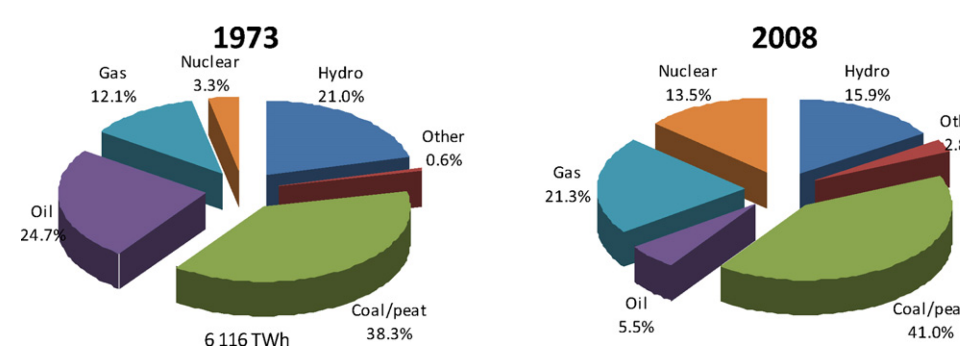


Fig. 2. 1973 and 2006 fuel share of electricity generation (excludes pumped storage). Other includes geothermal, solar, wind, combustible renewables and waste, and heat. *Source*: IEA [34].

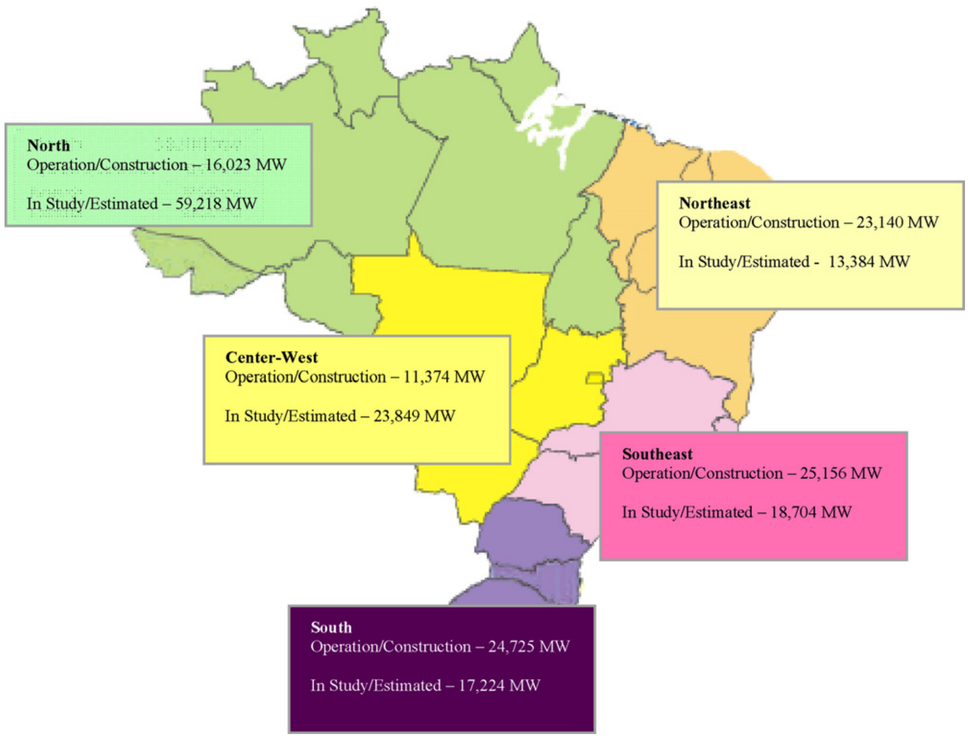


Fig. 3. Brazilian hydroelectric potential—2010. Numbers are in metric system notation.
Source: The author's own material based Eletrobras, SIPOT (2010) [2].

At a glance, it is possible to observe a significant concentration of hydroelectric energy generating in the basins located in the South and Southeast regions of Brazil, next to the largest consumer regions, and an under-utilization of the hydroelectric potential of North and Mid-West Regions, where these resources are abundant.

Brazil holds the greatest reserves of surface water on the planet, about 19.4%, and one of the world's greatest potential water resources. However, it is not in a comfortable situation in terms of the availability of water resources and the location of the demands for its consumable and non-consumable water [5]. In fact, about 90% of the water is found in low-density drainage basins from the Amazon and Tocantins rivers, while about 90% of the population is supplied by the rest of the country's water resources.

Due to the large proportion of hydroelectric power stations in the Brazilian power grid, the generation of electric power in the country is highly dependent on the hydrological cycles of drainage basins. As there is a regional imbalance in water availability – which may be seen in the recurrent droughts in the Northeastern region, the degradation of rivers and soils in the Southeastern region, the socio-environmental risks of each region and the rapid growth in demand for water and power throughout the country – both new and old hydroelectric enterprises are, to a greater or lesser extent, vulnerable to climate change.

The risk of future global climate change, that is, of additional warming of the planet, may alter the hydrological cycle, and, in turn, the water regime and availability of water in the drainage basins. In fact, different changes in temperature lead to changes in atmospheric pressure and wind patterns. Therefore, changes in rainfall patterns are to be expected.

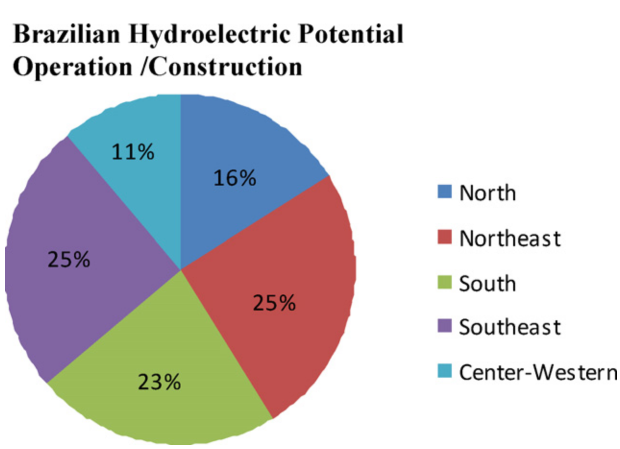


Fig. 4. Brazilian hydroelectric potential – in operation/under construction – 2010.
Source: Eletrobras, SIPOT (2010) [2].

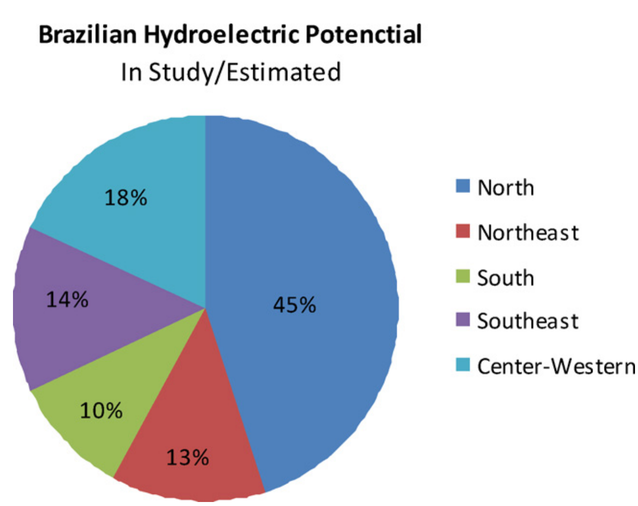


Fig. 5. Brazilian hydroelectric potential – being studied/estimated – 2010.
Source: Eletrobras, SIPOT (2010) [2].

Predictions for global sea level increases for 2099 indicate figures ranging between 18 and 59 cm, depending on different greenhouse effect gas emission scenarios. Occurrences of El Niño Southern Oscillation (ENSO) phenomena have been more frequent, longer and more severe over the last 20–30 years than they were during the preceding hundred years [6].

Thus it becomes important to carry out studies on predicting and evaluating climatic vulnerability in the generation of electric power in Brazil, with an emphasis on the assessment of water flow to hydroelectric power plants through climatic and hydrological prediction, both vital tools in the definition of scenarios in which hydrological risks (and consequently power shortage risks) can be anticipated.[1]

3. Impacts, vulnerability and adaptation to climate change

Assessments from the Intergovernmental Panel on Climate Change (IPCC) indicate that developing countries are among the most vulnerable to changes in climate. The IPCC also claims that the greater the difficulty a country has when dealing with the natural variability of climate and its extreme events, the greater the effort it will to make when adapting to climate change [7].

The impacts of climate change are not equally distributed among regions and populations. In fact, individuals, sectors and systems can be affected or benefited in greater or lesser measures. Thus, this relative pattern of distribution of climate vulnerability may vary in magnitude and intensity according to each affected region's geographical location, weather, social, economic and environmental conditions and infra-structure.

According to the IPCC [8], climate vulnerability can be defined as "the degree of susceptibility (or incapacity of response) of individuals or systems to adverse effects of climate change, including climate variability and extreme events".

The impacts resulting from changes in climate are directly connected to the vulnerability to which natural and human systems are exposed. Learning to deal with vulnerability, and especially with sensitivity to its impacts and capacity of adaptation to them, will be the most efficient way to mitigate the problem of climate change. For this reason, it becomes important to define methods and strategies to direct studies and research in this area, and also to implement those in the different regions affected.

The most relevant characteristic of climate change, with regard to vulnerability and the adaptation of water resources, is related to noticeable alterations in the variability of hydrological systems and extreme events, and not simply to average tendencies in climate change. Adaptation is an important factor in climate change and must be dealt with in two ways: assessment of impacts and vulnerability, as well as the development and implementation of strategies and concrete measures in risk management [9].

Most social sectors, regions and communities are reasonably well adapted to average conditions in climate change, particularly if the changes are gradual. However, in some sectors losses resulting from extreme climate variations are substantial and growing. These losses indicate that autonomous adaptation has not been sufficient to prevent damage associated with variations in climate conditions. Communities have shown themselves to be more vulnerable and less adaptable to climate changes, especially in terms of extreme events.

3.1. Effects and climate vulnerability on hydrology and water resources: IPCC evaluations

According to the IPCC [8,10,11], the effects of climate evolution on the flow of watercourses and the refilling of aquifers vary according to the regions and climatic scenarios that are created, especially regarding variations in projected rainfall. In projections carried out so far, the results for South America do not show agreement in flow projections, in the first place because of the different rainfall projections, and in the second place due to the different projections regarding evaporation, which may counterbalance the rise in precipitation. In general, the variations projected for the yearly average surface flow are less reliable than those based on temperature increase, mainly due to the fact that the evolution of rainfall varies widely for different projected scenarios.

At the level of drainage basins, the effect of a given climate change will vary according to the physical properties and vegetation of each basin, to which are added the alterations in the land cover (land use).

One third of the world's population – about 1.8 billion people – live today in countries and regions that suffer from medium and high levels of water stress.[2] According to projections from the United Nations, global demographic growth will place about 5 billion inhabitants in the same situation by 2025.

Thus, the predicted climate change may have a negative effect on the flow of rivers and on the refilling of groundwater reservoirs and aquifers in many countries which are exposed to water stress.

If water demand is generally increasing due to demographic growth and economic development, it is however decreasing in certain countries due to more efficient utilization practices.

Climate change will probably not exert a strong influence on water demand in cities and industries in general. However, it may have a considerable effect on the consumption of water for irrigation, which depends on the way evaporation is counterbalanced or accentuated by rainfall variations. A rise in temperatures, and consequently an increase in agricultural losses by evaporation, will normally represent an increase in demand for irrigation water.

Floods may increase in extent and frequency in many regions due to the increase of extreme rainfall events, increasing river flow in most zones but also facilitating the replacing of underground water in certain flood plains.

Changes in the soil may accentuate these phenomena. During low water periods the level of water streams will drop in several regions because of increased evaporation, the effects of which may be aggravated or neutralized according to rainfall levels.

Projected climate change may contribute in some areas to a lower quality of water resources—raising its temperature and increasing the pollutant load deriving from surface water flow and the overflowing of sewage treatment stations and sewage pipes.

In regions where lower rainfall levels are predicted, accompanied, therefore, by a drop in river flow, the quality of water will probably also decrease due to reduced dilution of the sewage pumped into rivers.

[1] It is convenient, in longer time scales, to make a distinction between climate change and natural climate variability: climate change is the systematic tendency or variation in a given sense, of climate parameters. It may occur due to systematic change in the radiative forcing of the climatic system or by anthropogenic action. Climate variability is inherent to the climatic system and presupposes alternation, that is, the superposition of cyclical or semi-cyclical variations. The detection of a tendency in climate requires, therefore, that the breadth of the natural variability be quantified. For this, a great variety of data and results of atmospheric models must be utilized [35,36].

[2] A classification of water stress zones is proposed by Alcamo et al. [32]: zones without water stress—water withdrawals (demands) are below 0.1 of water availability (average); zones of low water stress—water withdrawals (demands) are between 0.1 and 0.2 of water availability (average); zones of medium water stress—water withdrawals (demands) are above 0.2 and below 0.4 of water availability (average); zones of high water stress—water withdrawals (demands) above 0.8 of water availability (average).

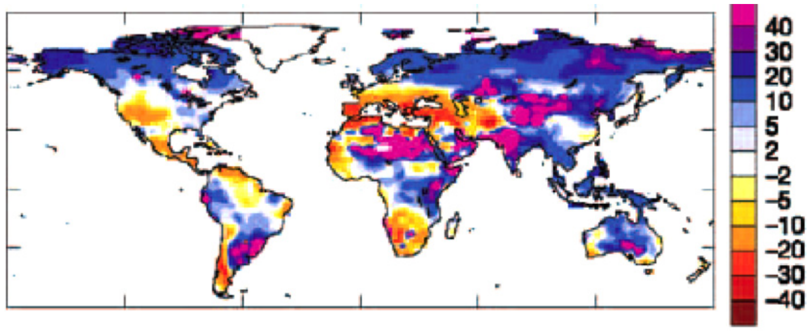


Fig. 6. Change projections in river outflow levels until 2050 (average from 12 models from IPCC AR4, scenario A1B).
Source: IPCC [10].

Special attention must be given to less well-regulated drainage basins, because they do not possess hydraulic structures, as well as to those which have already suffered extreme events, droughts and floods, and also to those which are carelessly exploited, with recurrent problems of pollution and water shortage, among other issues. In the case of unregulated systems which do not possess hydraulic infrastructure of sufficient quality to attenuate the effects of hydrological variability on the quality and quantity of water, vulnerability is higher. In the case of drainage basins which are exploited in a disorganized, non-sustainable way, the various users of the water and soil create additional restrictions which accentuate vulnerability to climate change.

However, it is possible to apply management tools to water resources, namely the integrated management of drainage basins, with a view to facilitate adaptation to the hydrological effects of climate change and to attenuate the different forms of vulnerability within each basin.

It is common nowadays to manage water supply (structural protection against floods, building of levees, use of water-storage zones and improvement of infra-structure for water withdrawal and distribution) instead of managing water demand (i.e. influencing the behavior of water users with a view to reducing losses and better managing the consumption of water in the drainage basin).

3.2. Projections for regional climate change and their limitations in terms of water resources

Projections for climate change on a regional level in terms of water resources, that is, predictions related to anomalies in rainfall on drainage basins in Brazilian territory, vary markedly from one model to the other. For example, according to the models from the Hadley Center (England), variations in average surface flow projected for 2050 in the Paraná river basin, assuming an increase of 1% in CO_2 concentration, appear as positive in the HadCM3 model (+50 to 150 mm/year in the basin's margins) and as negative in the HadCM2 (−50 to 150 mm/year in the basin's margins) [8,11]. The models are more ambiguous in the Southern Hemisphere due to its hydrometeorological observation network being smaller and more recently established than that of the Northern Hemisphere.

In Fig. 6 we present the results for the river flow projections for 2050, showing the average of the 12 models used by the IPCC in its 2007 report on the A1B scenario. According to these projections, we would have outflow decreases in part of the Amazon and Tocantins river basins, which would be worrying, especially for new enterprises aiming to establish themselves in these basins with high hydroelectric potential. However, in terms of the Paraná river basin, we would be able to maintain the tendency for outflow increase, which would favor, above all, the hydroelectric power plant structure already installed in the region, such as the Itaipu Binational Hydroelectric Power Plant and the Porto Primavera Hydroelectric Power Plant.

3.3. Changes in rainfall and river flow patterns in South America

The Brazilian Power Grid is highly dependent on short and medium-term water availability for the generation of 'firm energy'[3] and, therefore, for the guarantee of meeting demand. This system has been planned based on estimated-failure probability models, using historical series of flow patterns dating back to 1930 and to which are added yearly new sets of data from the national hydrometeorological network, currently managed by the Brazilian National Water Agency (ANA).

An increasingly integrated hydroelectric energy generation system considerably reduces the risks of not meeting energy demands should a given drainage basin suffer from an occasional dry spell. However, considering that most Brazilian power plants are located in the Paraná river basin, more than 55% of the country's present available generation capacity is subject to the same climatic vulnerabilities. We must, therefore, seek to improve the models for projecting streamflow patterns in the short- and medium-terms.

According to studies by IPH/UFRGS (Hydroelectric Research Institute from the Federal University of Rio Grande do Sul) and IAG/USP (University of São Paulo Institute of Astronomy, Geophysics and Atmospheric Science), since 1970 the Mid-West, South and Southeast regions have presented average river flow patterns approximately 30% higher than those of the preceding period (1940–1970). If this increase is permanent, it would be possible to reassess the firm energy capacity of the power plants, in other words, it would be possible to generate more energy with the capacity already installed, and with a smaller risk of failure [12].

Increase in streamflow patterns occurs due to two factors [12]:

- Increase in rainfall levels in the regions of Brazil referred to;
- Changes in the use of land in the same regions.

In the first case, the changes may represent a type of variability that, in the medium- and long-terms, will tend to change in the sense of reducing quoted generation capacity and average production levels.

In the second case, the increase would be permanent, and, therefore, would to a certain extent represent an energy gain, despite other environmentally harmful aspects.

[3] The 'firm energy' of a hydroelectric power plant corresponds to the maximum continuously produced energy that can obtained at that plant, assuming the lowest baseflow period registered in the history of streamflow patterns for the region in which it is built.



Fig. 7. South America—rainfall patterns from 1960 to 2000. *Note*: The circles indicate a tendency to reduction and the crosses a tendency to increase in rainfall. Symbols in bold are used to indicate more accentuated tendencies.
Source: IPCC [11].

According to the results obtained from the IPCC Workgroup 2 Report of 2007, the rainfall patterns in South America between 1960 and 2000 reinforce the thesis of increased rainfall in the River Plate basin and a decrease in the same values in the Chilean and Peruvian Pacific. In other areas the signs are not clear (see Fig. 7).

4. Conflicts, impacts and vulnerabilities in generating hydroelectric power

An aggravating factor in the Brazilian experience of using its hydroelectric potential concerns the great diversity found among the country's regions in terms of the availability of water. While droughts are a recurrent phenomenon in the Northeastern *sertão*, in the Southeast it is industrial and urban pollution, allied to river silting, that are the worrying trends. Also, further South there is more concern with agricultural production and cattle-raising, which are responsible for a diffused type of pollution of the surface and underground bodies of water that is difficult to control. Even in the planet's largest drainage basin there are problems arising from demographic expansion and unplanned settlements. Some of these are specific, such as the pollution of *igarapés* [streams originating in forests—trans.] and rivers that pass through urban areas, and others affect whole regions, such as the transmission of diseases by water and the decrease in water quality in smaller communities during the low-water period.

Thus, it is important to highlight that, in the medium- and long-term usage scenarios for Brazilian drainage basins, demand for water will tend to increase as a function of demographic growth, and above all, of economic development. Fig. 8 summarizes this delicate scenario of conflicts between energy, environment and water resources.

4.1. The Amazon river basin—water resources, climatic vulnerability and variability and main water usage conflicts

The continental Amazon River basin is the world's largest drainage basin, approximately 61,000,000 km^2 in area. Located in the intertropical zone, it receives an average of 2460 mm of rainfall every year. Average streamflow at the mouth of the Amazon River at the Atlantic Ocean is an estimated 209,000 m^3/s [13].

According to the results of the hydrology and geochemistry of the Amazon River Basin Project (HiBAm), the Amazon River Basin is affected by climatic variability caused by the El Niño Southern Oscillation (ENSO), which causes a significant decrease in rainfall [14,15]. The impacts of this specific instance of climatic variability on the hydrology of the Amazon River and its main tributaries have been studied by several authors [16–18], but these results are in part invalid due to the fact that they do not consider the phenomenon of some hydraulic blockages along the main course of the Amazon [19]. The impact of this climatic variability on erosion and on the flow of objects transported throughout the Amazon River basin remains to be discovered.

Among the certainties and uncertainties regarding the hydrometeorological cycle of the Amazon River basin are the following:

- Rainfall variability is relatively understood for the Brazilian Amazon [16,20], as well as in the Tropical Andes [21–23]. However, there is still a zone that has not been thoroughly studied or understood (between Southern Latitude Parallels 5 and 25), since it is connected, a priori, to the Amazon Plains (Llanos) of Bolivia, Peru and the extreme West of Brazil [24–26].
- The current hydrological regimes are understood for the rivers of the Bolivian and Brazilian Amazon, thanks to the data surveys provided by the PHICAB and HiBAm programs [19,27]. However, there is practically no information regarding hydrology and erosion in streams in the Tropical Andes (Colombia, Ecuador and Peru), and that has led to holding up the process of hydrological modeling of the Amazon Basin as a whole. The ENSO–hydrology relationship has been little explored for the Amazon River and some of its major tributaries [17]. To sum up, it can be said that the impact of climate variability on hydrology in the whole of the Amazon Basin is still fairly unknown.

4.1.1. Socio-environmental restrictions on the use of the hydroelectric potential of the Amazon Basin

The building of power plants in the Brazilian Amazon was begun in the 1970s with the installation of the Coaracy Nunes Power Plant in the state of Amapá in 1975. The plant generates 40 MW of power and uses 23 km^2 of flooded area. Since then, six hydroelectric power plants have been built in the area, amounting to a total of 6050 MW of generated power and 7600 km^2 of flooded area. The socio-environmental impacts of implementing these enterprises in the planet's largest rainforest ecosystem, which is also an area of high cultural and biological diversity, are the basis for studies and assessments that have been guiding new enterprises.

Among the cases studied, that of the Tucuruí Power Plant, located in the Tocantins River basin in an area of tropical rainforest, is certainly one of the most significant ones. It is the plant that generates the most power and inundates the largest area among those built in the region (4240 MW and 2800 km^2, respectively), having dislodged 4407 families.

Construction started in 1976 and the plant was put into operation in 1984, initially aiming to generate electricity for the towns of the Eastern Amazon region to stimulate occupation of the area and encourage the development of the Northern region of Brazil. It also endeavored to facilitate navigation in the region's rivers through the use of locks. However, the enormous mineral potential of the area attracted electricity-intensive industries to the region, especially aluminum companies, which require high levels of electricity. To satisfy these demands, the Tucuruí power plant also provided power for the region's industrial sector. Currently, the plant provides 50% of its output for industry and uses the other half to provide electricity for the states of Pará and Maranhão.

The lack of specific environmental legislation at the time, the disrespect for legislation that was in force and the lack of data regarding the region have brought about a series of impacts, expected or otherwise. The Brazilian power sector has learned much from Tucuruí.

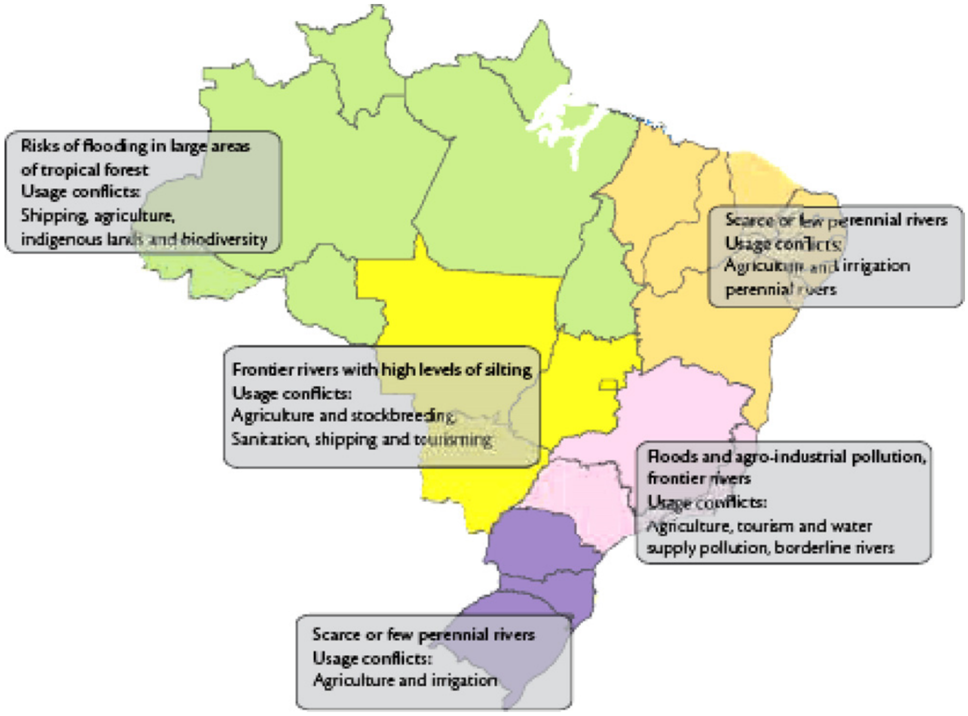


Fig. 8. Restrictions and usage vulnerabilities of the use of hydroelectric potential per region.
Source: The author's own material.

Among the unexpected impacts, the following stand out: isolation of the river-dwelling populations after the filling of the reservoirs; irregular and disorganized settlements; water usage conflicts; lack of infra-structure; severe proliferation of flies; intensification of predatory timber extraction; loss of fishing zones downstream from the dam; appearance of large schools of fish above the dam; enormous animal losses with the filling of reservoirs; emission of greenhouse effect gases from the surface of the dam lake; re-settlement in areas unsuitable for agriculture; high level of abandonment of allocated dwellings, and the sale of these; pressure on the local landowning structure; destruction of social bonds of the indigenous communities that lived in the area; selective power supply, with lack of service to the populations affected; population under-qualified for the jobs offered in the region; conflicts between commercial and small-scale fishing, and problems regarding the amount to be paid as compensation to those who had their homes flooded. Among the expected impacts, the loss of the region's rich biodiversity is worth emphasizing [5,14,28] (Fig. 9).

It is important to highlight the important technical breakthroughs achieved during the latest projects for hydroelectric power plants in the Amazon Basin, in other words, there is a clear concern on the part of both public and private entrepreneurs in the power sector in building smaller reservoirs for power plants, as can be seen in the Santo Antônio (3150 MW) and Jirau (3300 MW) power plants on the River Madeira, with estimated flooded areas of 271 and 258 km^2, respectively, as well as the Belo Monte plant, with an estimated flooded area of 400 km^2 and generated power capacity of 7500 MW [29] (Table 2).

With regard to global issues, the Amazon Basin has a fundamental role in the climatic dynamics and hydrological cycle of the

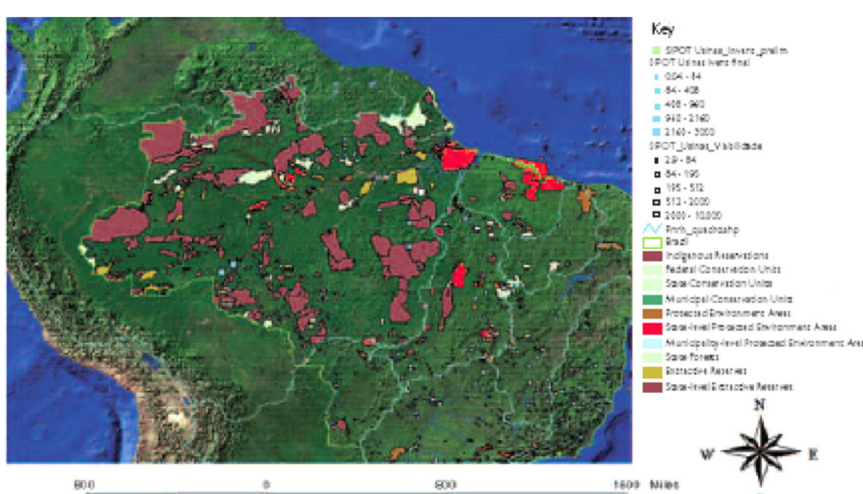


Fig. 9. Amazon and Tocantins River Basins – hydroelectric power plants (already planned and in study) and conservation units/indigenous reservations.
Source: Author's own material.

Table 2
Power plants in the Amazon Region – reservoir area/plant generated power ratio.

	Power plants in the Amazon Region	Reservoir area (km^2)	Reservoir area/generated power ratio (km^2/W)
Balbina	2360	250	9.44
Samuel	584	217	2.69
Manso	387	210	1.84
Tucurul			
Stage 1	2414	4000	0.61
Stage 1		8000	0.3
Jirau	258	3300	0.08
Santo Arconio	271	3150	0.086

Source: FURNAS [29].

planet. The basin represents approximately 16% of the world's surface freshwater stocks, and, consequently, contributes greatly to the rainfall and evapotranspiration regimes in South America and the whole world. Regional and global changes have caused changes in the climate and hydrology of the region: namely, changes in the use of the soil, with the conversion of more than 700,000 km^2 of rainforest into pasture, as well the global climate warming phenomenon, which has registered increases in average temperature of 0.6–0.9 °C over the last hundred years. Actually, marked changes in temperature may lead to other changes in the environment, including the intensification of the global hydrological cycle, which will in turn lead to more impacts on water resources at regional levels. In fact, different changes in temperature in the atmosphere, continents and oceans lead to changes of atmospheric pressure and wind patterns, therefore, we may expect changes in rainfall patterns, as has been predicted by the mathematical models for global climate change prediction of the Hadley Center for 2050, which predict average reductions of 150–250 mm/year in rainfall in the area.

It should be pointed out that, if the occurrence of anomalous increases in Surface Temperature in the Pacific and Atlantic Oceans intensifies, rainfall, and consequently streamflow levels will be reduced. In fact, in terms of the Pacific Ocean, "the occurrences of El Niño have brought events of extreme lack of rain, and, consequently, low discharges into the rivers in the region, especially in the Northeastern part of the Amazon". Tendencies to drier conditions were observed during the El Niño events of 1903, 1912, 1925–26, 1982–83, 1986–87 and 1997–98. Regarding the Atlantic Ocean, according to the Brazilian Center for Weather Forecasting and Climate Studies (CPTEC/Inpe) and the Brazilian National Meteorology Institute (INMET), during the period from September 2004 to September 2005, the Sea Surface Temperature was 0.5–1.5 °C above the average for the Northern Atlantic Ocean, in other words, an abnormal persistent warming phenomenon was registered. This phenomenon, possibly responsible for the 2005 drought in the Amazon, eventually altered the currents of humid air mass in the Amazon region, especially in important areas of the drainage basins of the Solimões, Negro, Madeira, Juruá and other rivers [30]. As to hydroelectric potential, the tendency to create reservoirs with smaller capacities, as mentioned above, will leave the region more vulnerable in terms of hydroelectric generation in years of water deficiency.

5. Adaptation measures in the Brazilian hydroelectric system and in water use to the risks of global climate change

Given the uncertainties of the current climatologic models when predicting future rainfall patterns in the Brazilian drainage basins, the recommendations made here are concentrated above all on reducing the vulnerabilities already detected with a view to expanding and sustaining the generation of hydroelectric power in Brazil.

5.1. Conflicts between hydroelectric energy and other users of water resources

The occurrence of extreme events, such as droughts and floods, more often and more severely will increase conflict among water users in the various drainage basins of Brazil. In terms of hydroelectric enterprises specifically, the increase in demand for water resources – in absolute terms and in their various forms – will require a more profound knowledge of the area where those enterprises are, as well as constant supervision of generating conditions, and not only in the power plant or in the reservoir areas. Hydrological balance will have to become more precise, surveys regarding environmental and economic impacts will have to be more detailed, etc. To sum up, the power plant's social responsibility towards the river-dwelling peoples and other users will tend to increase. The challenge in hydroelectric power generation is including in its planning new ideas—and, therefore, new competences that are often very different.

5.2. Conflicts between hydroelectric energy and other users of the land

Demographic growth and expansion of occupation (organized or not) of Brazilian territory tends to increase the number of individuals affected by hydroelectric enterprises, who then gain political power when making their demands. This means the process of making a project viable and putting it into practice becomes an extremely critical stage, since it now depends not only on long-term financing but also on increasingly longer negotiations, with higher transaction costs and fewer guarantees of success. It is important to revise the laws defining the compensation criteria for individuals affected by hydroelectric undertakings. For instance, there is no legislation today regarding populations and municipalities downstream from dams, nor regarding specific groups such as indigenous populations.

5.3. Multiple and integrated management of reservoirs

The increase in frequency and intensity of extreme events, such as the anomalous warming phenomena of the Pacific (El Niño) and Atlantic Oceans, require a more flexible approach to the management of reservoirs, apart from the mere optimization of hydroelectric power generation. Measures must be taken to reduce the negative impacts and increase the benefits to the basin and to the users involved. Such measures are taken both at the moment when the decision is made to build the power plant as well as when deciding how to manage its reservoir, and as a consequence many social costs may finally be imposed on



Fig. 10. Energy exchange between regions. SE/CO—Southeast/Midwest; S—South; NE—Northeast; N—North; MAN/AP—Manaus/Amapá; IV—Ivaiporã; It—Binational Itaipu Hydroelectric Plant; AC/RO—Acre/Rondônia; BM—Belo Monte; TP—Teles Pires/Tapajós; IMP—Imperatriz.
Source: EPE [1,31].

the generating company by the Government, a tendency already observed internationally. Therefore, there should be an increase in investments previously considered marginal to the main line of business, such as conservation of vegetation growth, regulation of streamflow from the rivers and their tributaries, controlled disposal of industrial waste, the acquisition of hydrological information and the establishment of orderly use of the land in the drainage basin.

5.4. Reservoirs and flood control regularization

The hydraulic operation of reservoir systems is always directed towards energy optimization and to meet the multiple uses of water. Not only benefits the other water users, as water supply, navigation and agriculture, but also the reservoir accumulation are important for flood control. Thus, to preserve the cities downstream of the project.

From the perspective of energy optimization, the existence of reservoir accumulation provides important energy exchange between regions of the country, made through the National Interconnected System, as illustrated in Fig. 10.

The National Electric System Operator – ONS – forwards annually the Report Rules for Operation of Flood Control for each of the systems of reservoirs included in the Annual Plan for Flood Prevention to the National Agency of Electrical Energy – ANEEL – and to the National Water Agency – ANA – for evaluation and then makes it available to the agents operating. The Annual Plan for Flood Prevention results from the study of flood prevention systems in reservoirs, in which are determined physical resources, known as volumes of waiting for the flood control. These resources are part of the working volumes of the reservoirs, below the maximum normal operating, to be used in flood control. The allocation of expected volumes in the reservoirs of hydroelectric exploitations can generate impacts in the energetic operation of the National Interconnected System (SIN), since it restricts the maximum storage capacity of reservoirs. These volumes are dependent on the restrictions imposed by irregular occupations in troughs in the river downstream of development. Every year, despite the impact in energetic operation, these restrictions are reassessed.

5.4.1. North–South Interconnection

Until 1998, the Brazilian Power System was composed of two subsystems, the North/Northeast and the South/Southeast/Midwest, which operated separately until the entry into operation of the first circuit of North–South Interconnection, forming the National Interconnected System (SIN). Currently (Fig. 11), this interconnection is formed by three 500 kV circuits, being two circuits since SE Imperatriz until Serra da Mesa and one circuit since Itacaiúnas until Serra da Mesa. Studies of generation expansion indicate requirements for expansion of capacity for exchanges between the North and Southeast/Midwest regions, whose alternative transmission expansion, contemplating including the influence of connecting the AHE Belo Monte in northern, are currently being reviewed by the Energy Research company.

5.5. New institutional and regulatory arrangements for the generation of hydroelectric power

Reducing vulnerability in hydroelectric enterprises requires above all a major acceptance of those enterprises by society. It has to be accepted that the complexity of the most recent projects is far greater than that observed until the 1980s, essentially due to changes in legislation. Today numerous institutional arrangements and political connections must take place before the decision is made to invest in the building of a dam, a hydroelectric power plant or a large thermal power generation center. Authorizations must be obtained from regulatory agencies in the power, water and environmental sectors, as well as agreements that must be made with governors, mayors and local community associations. The current regulatory requirements not only demand a series of environmental licenses for the exploitation of hydroelectric potential and permits for the use of water, but also impose heavy fees for its use, consumption and discharge, as well as obligations regarding the acquisition and provision of hydrological information. It is no wonder that, of the several projects projected for the power sector in the 1980s, few were not cancelled, postponed or completely reformulated during the 1990s.

5.5.1. New institutional and regulatory arrangements for the generation of hydroelectric power

The National Energy Agency (ANEEL) and the National Water Agency (ANA) published in October 2010, in the Official Gazette, the Joint Resolution no. 003, which expands the scope of monitoring the country's water resources. The Joint Resolution no. 003 establishes the conditions and procedures to be followed by dealers and authorized to generate hydroelectric power for the installation, operation and maintenance of hydrometric stations in order to monitor rainfall, limnimetric, fluviometric, sedimentometric scales and water quality associated with hydropower development, and indicates other providences. This was the first joint standard between regulatory agencies. Besides the parameters defined in the former Resolution 396/1998, which was repealed, will be checked the level of sedimentation in lakes and the quality of water used in hydropower projects. Other innovations included in the resolution will allow the constant and remote transmission of information to ANA, responsible for data management. This way, the oversight agency may act more efficiently. The dealers and authorized agents of generation covered by this current regulatory will have to send to the National Water Agency (ANA) the annual report by April 30 of the following year, according to the model defined by this agency.

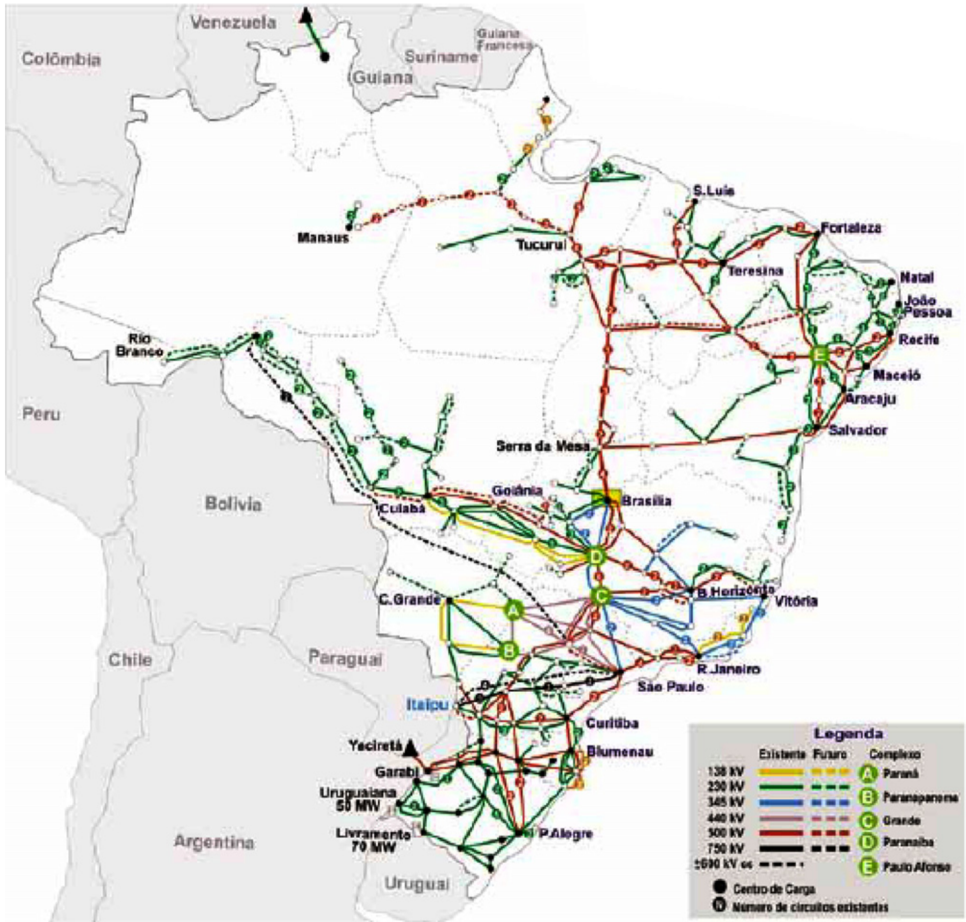


Fig. 11. Transmission lines of the National Interconnected System – SIN.

Source: ONS [33].

5.5.2. Technological and economic opportunities in the electricity generating sector

The reduction of vulnerability in the generating sector of the Brazilian power grid depends strongly on integration with other sources of energy and enterprises on several levels. In other words, an additional challenge to be considered concerns the changes that have occurred in the generation industry itself, both in the technological and economic fields. Technical-economic paradigms, such as those of large power plants, have been strongly opposed for instance, and new business opportunities have arisen in the field of establishing and operating small power stations. We see today a proliferation of small power plants based on small streams and waterfalls, the reutilization of biomass residues, wind farms in coastal areas and even aviation-derived turbines fueled by natural gas that can be installed in city buildings. The economic impact has been almost immediate: less dependent on large-scale profits, the new generating technologies have enabled new products to enter the market, significantly improving competition. This move has been reinforced by the general deregulation of infrastructure services in developing and developed countries. In this completely remodeled scenario, the list of most important actors in the process includes some large multinational groups, working from the basis of the planetary scale of their operations, as well as growing economies (either in breadth or scope) that are emerging among the different infrastructure sectors. But the new actors in the spotlight are companies or conglomerates on a regional or local scale, which have entered the energy generating business encouraged by the availability of smaller units that can be placed near consumer centers, built more quickly and in modules, are fairly flexible in their operation and can work if necessary only during peak hours.

Another factor in favor of these smaller enterprises is the pressure for profitability that appeared in the 1990s and began with speculation in stock markets throughout the world. In the infrastructure sector, and especially in the energy generating sector, the *leitmotiv* has become speed of return on investment and the mitigation of risks, two concepts that perfectly agree with the philosophy and cost structure of these new projects.

5.6. Energy integration with neighboring countries

5.6.1. Current status

Besides the Binational Itaipu Hydroelectric, involving Brazil and Paraguay, the current setup includes interconnections between Brazil and Argentina, Uruguay and Venezuela.

With Argentina, Brazil has two electric interconnections, both made by converting frequency 50/60 Hz, back-to-back type. The first converter, with power equal 50 MW, is located in the city of Uruguaiana, Brazil, and the second, with power equal to 2200 MW, located in the city of Garabi, Argentina.

The interconnection Brazil–Uruguay existing is accomplished through a 50/60 Hz frequency converter, back-to-back, with power of 70 MW, located in Rivera (Uruguay) and the interconnection between Brazil and Venezuela is accomplished through the substations of Boa Vista in Brazil and El Guri in Venezuela, and the system capacity of 200 MW.

5.6.2. Integration possibilities

Brazil is seeking to establish agreements with bordering countries looking for regional energy integration. As these agreements are going to solidify, the projects are to incorporate the planning studies of the expansion of the supply sector. Among them, the following projects are outstanding:

- Inambari Power Plant, with about 2 GW of power, whose conclusion of the feasibility study is scheduled for the first half of 2011. Peru has hydroelectric potential estimated between 6 and 7 GW [31].
- Cachoeira Esperança Hydroelectric Power Station, with power of 800 MW, being implemented in Bolivian territory, between Inambari (Peru) and the Brazilian power plants in Madeira River (Santo Antônio and Jirau, in Brazil).
- Garabi and Panambi Power Plants, binational enterprises located in Uruguai River, between Brazil and Argentina, in inventory final phase and with installed capacity of 1137 MW and 985 MW of reference, respectively. Currently are being defined the parameters for the hiring of feasibility studies.

Are also being performed hydropower inventory studies in Guyana, whose potential is about 7.5 GW, being possible to negotiate a construction of one or two power plants in this country to import part of the electricity to be produced [31].

It is essential that opportunities for regional integration are evaluated, either through new power plants, either through new transmission lines. However, we must remember that for the construction of hydroelectric plants in transboundary basins, e.g., Madeira, it is necessary to invest in monitoring stations and to create mechanisms for sharing of hydrological data.

6. Conclusion

Hydroelectric power plants in Brazil contribute 76.9% of all electricity generated in the country. Despite the large share of hydroelectricity, north of the country still has a great hydraulic potential to be availed, mainly in the Amazon basin. It is very likely that, due to increasing socio-environmental resistance, the future plants, especially those in Central and North West are practically built with no reservoir. As the Brazilian system has large storage capacity and being maintained the integrative role of the transmission system, this limitation can be bypassed. The Southeast reservoirs can still play the role of virtual reservoir of these run-of-the-river plants, however, there will be a need for greater participation of flexible thermal. It is noteworthy, though, that because of the run-of-the-river plants not having reservoirs and therefore the ability to regulate the flow of rivers cannot contribute to mitigating the problem of flooding. In period between 1997 and 2000, the Brazilian hydroelectric system lost its ability to reserve multiannual because of the implantation of the new model proposed for the electricity sector and consequent lack of building new plants. The existing reservoirs were then gradually being emptied, until the summer of 2000/2001, when the country had to ration power. There was then, an extraordinary accession and cooperation of society, that brought plenty of energy in market, due to reduced domestic demand, and also a great learning experience for the country.

During this period, the Brazilian electric sector planning has suffered a serious discontinuity of stoppage of the process of inventory studies.

Regional and global changes, such as changes in land use and interference with the climate change, with changes in temperature and in rainfall regimes, require the completion of studies to predict and assess the climate vulnerability to power generation sector, with emphasis on the assessment of inflows to the hydroelectric reservoirs by means of weather forecasting and hydrological, fundamental in defining scenarios in which the energetic and hydrological risks can be known in advance.

Given the importance of hydroelectricity in the Brazilian energy matrix, we should seek for extending the knowledge of the national hydraulic potential and, also, in neighboring countries in order to provide mutual and synergetic gains in the implementations of the new plants. The realization of joint inventory and feasibility studies of transboundary basins should be encouraged. It is possible to realize that, as source of information, only SIPOT – Hydraulic Potential Information System, from Eletrobras, presents an assessment of the national territory. A large share of this potential is located in Amazon and the major developments planned in the region are located in Madeira, Xingu and Tapajós rivers.

From the above, the implementation of the hydroelectric power stations in Brazil should reach a balance between the energy production and the socioenvironmental aspects and multiple uses of water resources.

In this sense, it is important to highlight some characteristics of hydropower in Brazil:

- Seasonal feature of the water input;
- High growth in energy consumption, particularly in the Northeast;
- Location of the new hydroelectric plants away from the consumption centers and with more stringent socioenvironmental restrictions.

Despite the advances made in view of socio-environmental projects, the relocation of people is still treated, in many companies, by the areas of real estate assets, and not under a broader view, involving the areas of environment. On the other hand, the need for regional integration has proved the most controversial issue currently faced by the electricity sector. In the poorest areas of the country, hydroelectric generation companies often are seen by the population as the state itself. The hospital set up to meet the staff of the Paulo Afonso Hydropower Plant (BA), for example, became the major reference center for public health care in the region of the São Francisco River. This symbiosis between Energy Company and the government resulted in difficulties, in the majority of dealers, in mapping regional integration programs that run away from paternalistic character and from municipalities local political actions where power plants are located. It is noteworthy also, that the municipalities have received over the past 20 years, the financial resources from financial compensation for the use of water resources, however, these rarely invest these resources in strategies unrelated to the treatment of the socioenvironment.

Some lessons were learned, such as:

- Future hydroelectric enterprises must be implemented with local and regional development goals from their very conception, not restricting themselves to the generation of power for enterprises that will bring benefits to other areas.
- The implementation of new hydroelectric enterprises must be preceded by the elaboration of a hydraulic inventory of the whole basin, incorporating not only the physical consequences, but also an assessment of all social and environmental impacts that will ensue.
- The importance of a prior assessment of the environmental impact of several different alternatives calls for the creation and fine-tuning of new mechanisms for public participation in all stages of projects for large dams.
- The implementation of hydroelectric enterprises must involve the evaluation and support of a drainage basin committee, which

should mediate negotiations between the various agents and water users involved in the process.

- The criteria for definition of the area directly impacted by the hydroelectric enterprise should be subject to legal scrutiny, and compensation rights should be offered to all involved. Such a study should not be restricted to the flooded area alone, and social control mechanisms should be created to make sure the financial resources invested are directed to the right place and used correctly.
- Scientific uncertainty concerning the magnitude and relevance of the environmental impacts and risks brought by the enterprise should be addressed by the adoption of the 'principle of caution' throughout all stages of planning, building and operating the project.
- Recognition, on the part of the entrepreneur, that social movements are legitimate voices in defining public policies and in taking decisions that affect their way of life.
- The need to ensure access to technical information, in language appropriate for laymen, concerning the project and associated impacts.
- The need to create permanent channels of communication between the entrepreneur and the communities affected by the enterprise throughout the entire cycle of the project.
- Promotion of integrated development actions for rural areas with an emphasis on renewable energy projects and improvement of quality of life for the population, taking into consideration ease of access to the benefits brought by the enterprises to the urban populations and the low rate of services rendered to the rural populations of the Amazon.
- The lessons learned should be of service in the planning, building and operation of other hydroelectric projects in the Amazon, so that these can contribute to the sustainable and participative development of the region and of the country.

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